Optik 139 (2017) 87–94

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

3D surface profilometry based on 2D S-Transform method with optimized window

Min Zhong [a,*], Feng Chen [a], Chao Xiao [a], Yongchao Wei [b]

[a] College of Optoelectronic Technology, Chengdu University of Information Technology, Chengdu 610225, China
[b] Academy of Flight Technology and Safety, Civil Aviation Flight University of China, Guanghan 618307, China

ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form 15 January 2017
Accepted 21 March 2017

OCIS codes:
150.6910
070.2590
100.2650
100.5070
070.4790

Keywords:
3D Sensing
S-Transform
Fringe analysis
Phase retrieval
Time-frequency analysis

ABSTRACT

S-Transform method can be regarded as an extension to the ideas of the Windowed Fourier Transform (WFT) method and the Wavelet Transform (WT) method, which gives consideration to both local frequency concept of WFT and the multi-resolution strategy of WT. It has been introduced in optical 3D shape measurement recently. However, the S-Transform method suffers from poor energy concentration when some kind of signal is treated with. In order to enhance energy concentration to provide more accurate estimation of the instantaneous frequency, a modification to the existing 2D S-Transform is proposed in this paper. Two additional parameters are introduced to respectively optimize the window width in x and y direction. The paper gives the expression of 2D S-Transform with optimized window and its performance in 3D surface reconstruction. The application of proposed method is demonstrated on both simulation and experiment by comparing with traditional 2D S-Transform method. The improved performance of optimized 2D S-Transform for 3D surface shape measurement shows its feasibility and veracity.

1. Introduction

The optical 3D surface shape measurement technology based on the structured light illumination with the characteristics of non-contact, fast speed, high precision, high efficiency and large information capacity has been widely used in military, industrial inspect, agriculture, medicine and space science [1–3]. Based on the principle of triangulation measurement, this technology can be divided into multi-frame fringe analysis technique and single-frame fringe analysis technique. Multi-frame fringe analysis technique extracts phase information from fringe patterns with known phase shifting values or unknown phase shifting values. The typical approach with high measurement accuracy for this technique is phase shift method [4–6]. It is more suitable to static measurement because more than three images are required to be captured to obtain the phase distribution. Nevertheless, single-frame fringe analysis technique can calculate phase distribution based on only one or two images that it can realize dynamic measurement. For this technique, there are some common methods applied in fringe analysis such as Fourier Transform method [7–10], Windowed Fourier Transform method [11–13], Wavelet Transform method [14–17] and S-Transform method [18–24].

* Corresponding author.
E-mail address: zm1013@cuit.edu.cn (M. Zhong).

http://dx.doi.org/10.1016/j.ijleo.2017.03.087

Fourier Transform method was firstly proposed by Takeda [7] in 1983. It is a global analysis and suitable to deal with stationary signal instead of non-stationary signal. Fringe pattern belongs to non-stationary signal. To get better phase distribution of fringe pattern, windowed Fourier transform (WFT), Wavelet Transform (WT) and S-Transform (ST) are introduced in this field. With a fixed window size, Windowed Fourier transform method [11] fails to give good reconstruction result for the measured object with sharp change in surface. In order to overcome this shortcoming, Wavelet Transform [14] employing the concept of scale is introduced in the demodulation of fringe pattern. This method has the characteristics of multi-resolution strategy and local analysis capability but it has no direct relationship with the Fourier transform spectra. S-Transform [18], a combination of WFT and WT with the capability of extracting single frequency component effectively, was introduced in the analysis of fringe pattern. This method has the advantages of both local frequency concept as WFT and multi-resolution strategy as WT. An important feature for this method is that it maintains direct contact with the WFT. The Fourier spectrum of input signal can be obtained via addition calculation for the S-Transform coefficients over spatial/time direction. S-Transform uses a Gauss window to extract the local signal, whose height and width can be adjusted to the local frequency component at each position. However, the S-Transform suffers from poor energy concentration when some kind of signal is treated with. In order to enhance energy concentration to provide more accurate estimation of instantaneous frequency, modification is introduced in the original 1D S-Transform method, recently. Pinnegar and Mansinha use a bi-Gaussian window to optimize the 1D S-Transform [25]. According to this idea, a modification to the existing 2D S-Transform is proposed in this paper. Two additional parameters are introduced to respectively optimize the window width in x and y direction.

Not only the demodulation of the fringe pattern is of importance, but also phase unwrapping algorithm play a significant role. Many algorithms have been applied to reconstruct the surface shape of measured object, such as flood phase unwrapping algorithm [26], cut-line method minimum spanning tree [27–29] and so on. Li [30] has provided a phase unwrapping method based on the amplitude value of wavelet transform coefficients, which can effectively avoid error transfer. Subsequently, Jiang [20] has introduced the 1D S-Transform coefficient into phase unwrapping operation. Similarly, in this paper, 2D S-Transform coefficients are applied in phase unwrapping operation to obtain a better reconstruction. The result shows that the optimized 2D S-Transform method achieves higher accuracy than the original 2D S-Transform method.

2. Principle of 2D S-Transform

2.1. Traditional 2D S-Transform

The definition of 2D S-Transform [21] can be expressed as

$$S(u,v,f_u,f_v)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}h(x,y)\frac{|f_u||f_v|}{2\pi}\exp\left(-\frac{(u-x)^2f_u^2}{2}-\frac{(v-y)^2f_v^2}{2}\right)\times\exp[-i2\pi(f_ux+f_vy)]dxdy \tag{1}$$

Where $h(x,y)$ represents the input signal under test. $S(u,v,f_u,f_v)$ is a four-dimensional matrix. $\frac{|f_u||f_v|}{2\pi}\exp(-\frac{(u-x)^2f_u^2}{2}-\frac{(v-y)^2f_v^2}{2})$ represents the 2D sliding Gauss window, whose sizes in x and y directions are respectively controlled by the instantaneous frequency parameters f_u and f_v. While the spatial variables u and v decide the center coordinates of Gauss window.

Eq. (1) can also be rewritten as

$$S(u,v,f_u,f_v)=[h(u,v)\otimes g_{f_u,f_v}(u,v)]\exp[2\pi(-if_uu-if_vv)] \tag{2}$$

Where

$$g_{f_u,f_v}(u,v)=\frac{|f_uf_v|}{2\pi}\exp\left(-\frac{u^2f_u^2}{2}-\frac{v^2f_v^2}{2}\right)\exp[2\pi(if_uu+if_vv)] \tag{3}$$

Symbol $\otimes$ represents a 2D continuous convolution operation.

One can obtain the 2D Fourier Spectrum of input signal $h(x,y)$ by averaging the 2D S-Transform spectra $S(u,v,f_u,f_v)$ over the variables u,v, that

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}S(u,v,f_u,f_v)dudv=H(f_u,f_v) \tag{4}$$